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ABSTRACT

Future United States Air Force (USAF) and National Air and Space Administration (NASA) space systems such as Space Based Radar (SBR), Space Based Laser (SBL), and Space Station will incorporate smart structures/skins as part of their active vibration control system to sense, evaluate, and damp out any natural and spurious vibrations and health monitoring system to sense any degradation to the structure. The concept called smart structures/skins is identified as one of the Project Forecast II technology areas. A smart structure/skin is defined as the embedment of sensors, actuators, and microprocessors in the material which forms the structure. One particular sensor that is being studied in depth is fiber optic. Fiber optics are lightweight, immune to electromagnetic interference, and are easily embeddable into composite material.

The Astronautics Laboratory (AL) is committed to develop and incorporate this technology into future space systems. This paper describes the current and future activities, both in-house and contractual at AL, in the area of smart structures/skins with emphasis placed on the role of fiber optics. Items to be discussed include, types of sensor and actuator systems, areas that future research and development need to address, and plans to incorporate smart structures/skins into future space systems.

1. INTRODUCTION

The Astronautics Laboratory (AL), formerly known as the Air Force Rocket Propulsion Laboratory (AFRPL), is located on the northeast corner of Edwards Air Force Base in California. With the change in name from AFRPL to AL also came a change in mission, as directed by both Air Force Space Systems Division and Space Technology Center, to develop not only propulsion technology, but also spacecraft vehicle technology. The AL has, over the last five years, been working in the area of spacecraft dynamics and control. These programs to develop spacecraft control are in response to the needs of future planned Air Force space systems such as the Space Based Radar and Space Based Laser. Such systems pose serious vibration control problems resulting from their large size and stringent precision pointing, shape control, and rapid retargeting requirements. An active control system capable of sensing, evaluating and damping out these structural vibrations is needed to control these space systems. On such control systems smart structures/skins were identified as an Air Force Project Forecast II technology. A smart structure/skin is defined as the embedment of sensors, actuators, and microprocessors in the material which forms the structure.

The AL is committed to develop and incorporate this technology into future space systems. They have been actively working in this area for the last two and a half years. What started out as one small feasibility contract in 1987 has blossomed into numerous contracts with various contractors and a major in-house research project. Presently, we have three ongoing contracts. The first and foremost contract for the AL is titled, "Advanced Composites with Embedded Sensors and Actuators" and was awarded to both TRW Inc. and Boeing Aerospace. A second contract titled, "An Investigation of Materials and Automated Production Methods for Smart Structures" was awarded to American Composite Technology. Finally, a third contract titled, "Composite Embedded Fiber Optic Sensors for Active Control of Space Structures" was awarded to Dynamics Technology Inc.

The in-house effort is divided up into five major tasks. The first task is the joint AL/NASA effort to develop smart struts with embedded fiber optic sensors. The second task is with Dr. Clarance Calder from Oregon State University and its objective is to explore the feasibility of embedding various sensors in graphite-epoxy composites to provide continuous information on the stress-strain state and the condition of the composite during its service lifetime. The third task is with Dr. David Jensen from Pennsylvania State University and its objective is to calibrate the performance of composite-embedded fiber-optic strain sensors. The fourth task is with Dr. David Kranbuehl from the College of William and Mary and its objective is to develop frequency dependent electromagnetic sensor (FDEMS) techniques for continuous insitu monitoring of the chemical-structural integrity of composite and composite parts during use in space and flight. A second objective is to demonstrate the capability of the FDEMS for quantitative non-destructive material evaluation of composite parts during exposure to atomic oxygen, thermal cycling, UV and high energy radiation, and stress-strain extremes. The fifth task is with Dr. Mike Gorman from the Naval Postgraduate School and its objective is to compare the new embedded sensor to conventional sensors such as accelerometers, strain gauges, etc..

2. CONTRACTUAL EFFORTS

The major contractual effort ongoing at the AL is titled, "Advanced Composites with Embedded Sensors and Actuators" (ACESA). This contract was awarded to both TRW Inc. from Redondo Beach, CA and Boeing Aerospace from Seattle, WA on a competitive basis with a downselection occurring after the first year of technical effort. The objective of this project is to design, fabricate, test and evaluate composite components with embedded sensors, actuators, and microprocessors for dynamic sensing and control of large space structures. A second goal is to determine the applicability of these sensors for health monitoring of the space structures. The technical approach is divided up into five phases. In phase I, a survey of needs, requirements, and designs will be performed. This will include work in the areas of actuators, sensors, and microprocessors and material systems compatible with space applications. Phase II will include the sub-scale test demonstration of the sensor and actuator components. The sensors and actuators will either be embedded into composite material or attached on metal struts (such as aluminum) to determine the applicability of the sensors and actuators chosen from phase I. Phase III will consist of optimizing fabrication techniques on sub-scale components with embedded sensors and actuators. Mechanical and environmental testing will also be performed on test coupons to determine any structural degradation caused by embedding the sensors and actuators into the composite material. In phase IV, full-scale smart structures will be fabricated at both the contractor's facility and at the AL. In Phase V, testing of the full-scale composite struts will be performed at the AL's Large Space Structures Test Facility called ASTREX. The payoff for this project will be an integrated, highly responsive, low weight, control and health assessment system for space structures which will be capable of achieving approximately a 10:1 increase in structural damping. The downselection for this contract was completed the first week in Oct 89 with TRW Inc. as the winner. They fabricated two subscale prototypes with piezoelectric ceramic sensors and actuators embedded into the composite material. The prototypes were 2in. square tubes, 60in. in length. TRW used a digitally programmable analog circuit to control the prototypes. Boeing fabricated a low frequency and a high frequency subscale prototype. The low frequency prototype had a fiber optic and a NiTiNOL sensor and a NiTiNOL actuator attached to it for control. The dimensions of this prototype are 6in. wide by $^1/_8$in. thick by 64 in. in length. The high frequency prototype had a NiTiNOL sensor attached to it and piezoelectric ceramic actuator embedded into it for control. The dimensions of the high frequency prototype are 6in. by 4in. rectangular tube, 64in. in length. Both contractors chose graphite/epoxy as the composite material for the prototypes. A final report from both contractor is being published and will be distributed the beginning part of next year. This final report will contain all of the results generated from the first year of technical effort which will encompass both phase I and II. TRW will continue for the next 33 months on the contract performing mechanical tests of the subscale prototypes and coupons to detect any strength or stiffness degradation due to the sensors and actuators embedded into the structure. Finally, they will fabricate key components of a sub-scale large space structure, integrate these components into the sub-scale structure which is located at the Astronautics Laboratory, and test the structure at a the ASTREX ground test facility here at the AL. This will demonstrate system performance using the embedded control system.

The second contract ongoing at the AL is titled, "An Investigation of Materials and Automated Production Methods for Smart Structures" and was awarded to American Composite Technology (ACT). ACT was awarded this contract under the Small Business Innovative Research (SBIR) Program. The technical objective of the phase I project was to investigate materials and automated production methods for smart structures. The goal was to optimize the material selection and component details in order to move from hand-made laboratory production techniques to reliable automated production techniques. The technical approach is divided up into three tasks. The first task was a survey of components which make up a smart structure such as the sensors, actuators, and control networks. The second task was the development of potential production methods for smart structures. The third task was to complete a trade study from the surveys and to select a design for further study. The phase I contract has ended and ACT is being selected for a phase II folow-on contract in which they will produce a composite structure with embedded sensors and actuators using automated production techniques.

The third contract ongoing at the AL is titled, "Composite Embedded Fiber Optic Sensors for Active Control of Space Structures" and was awarded to Dynamics Technology Inc. (DTI) from Torrance, CA. This contract is also a phase II SBIR. The objective of this phase II contract is the design and development of smart composite structures based on the interferometric fiber optic sensors. The final output of this contract will be the design and fabrication methodologies for embedded fiber sensor systems, their full-scale feasibility assessment and a sub-scale SDI smart structure operating under real-time active control and compensation. The technical approach is divided up into three tasks. The first task is embedded fiber optic sensor development which includes the design, fabrication, and testing of the composite structures and signal processing design and development. The second task is the engineering feasibility assessment which includes the system architecture design and analysis, advanced sensor and signal processing concept investigation, and the full-scale system requirements and reliability investigation. The final task is to fabricate and test the sub-scale demonstration test article. The final payoff of this contract is to develop new interferometric fiber optic sensors and demonstrate their performance in a typical sub-scale SDI structure.

3. IN-HOUSE EFFORTS

The in-house effort was started in Apr 1988 in order for the AL to develop technical expertise in the area of smart structures. The objective of the in-house effort is to design, fabricate, test, and evaluate composite components with embedded sensors, actuators, and microprocessors for dynamic sensing and control of large space structures. A secondary goal is to determine the applicability of using these sensors for health monitoring. The in-house project is divided up into five major tasks. The first task is the joint AL/NASA project. The technical approach for the joint AL/NASA project is divided into four phases. The first phase is to acquire the necessary equipment to embed sensors, actuators, and microprocessors into composite material. The second phase is to conduct processing science studies to determine the optimal composite material and design to use. The third phase is to fabricate, evaluate performance and mechanically test the sub-scale structures. The final phase is the integration of full-scale smart members into the AL ASTREX test article to determine system performance using smart structures. In this first task, we have embedded fiber optics into graphite/epoxy tubes and flat beams at the AL and tested them at NASA LaRC. We are using the Optical-Phase-Locked-Loop laser system developed by NASA LaRC for measuring strain and vibrations of the structures. We plan on embedding piezoelectric and NiTiNOL actuators in the fall of 1989 for active control of the structures. NASA LaRC is presenting a paper at this conference explaining the results accomplished during the last year.

The second task of the in-house effort is with Dr. Clarance Calder, and Tom Salzano from Oregon State University. The main objective of this project is to fabricate and test beam and tube specimens with various types of sensors embedded into them. The specimens will be fabricated at the AL and tested at Oregon State University. The specimens will be tested in cantilever bending for static strain measurements and the first few vibration modes will be characterized in dynamic tests. Some of the sensors which will be embedded into the specimens are piezoelectric crystals, strain gauges, strain wire, NiTiNOL wire and fiber optics. A comparison will be made between the different types of sensors in regards to performance, embeddability, and sensitivity. Also, as part of this task, Brad Yost from San Diego State University is examining the possibility of using strain wire for damage detection and characterization of composite specimens.

The third task is with Dr. David Jensen from Pennsylvania State University. The objective of this task is to calibrate the performance of composite embedded fiber optic sensors using a Mach-Zender interferometric system with results obtained from conventional sensors such as strain gages or extensometers. This research will demonstrate the capabilities of composite embedded fiber optic strain sensors in smart structures. The technical approach of this task is divided into five phases. Phase one will involve designing the test coupons. In phase two, the coupons will be fabricated with fiber optic sensors embedded in them. The third phase is to test one third of the test coupons in tension to failure while recording the strain using the optical interferometer and conventional sensors. This phase will calibrate the performance of the interferometer when measuring static tensile strain. The fourth phase is to test the second third of the coupons cyclically in tension to failure. This phase will identify any loss in strain transfer between the composite and the fiber optic sensor. The final phase is to test the last third of the coupons cyclically in tension and compression to failure. This phase will provide additional information between the loss in strain transfer between the fiber optic and the composite. The progress made to date is the completion of the (phase I). The composite design has a lay-up of $[0_3/90_2/0]_s$ with midplane symmetry. The optical fibers will be embedded between the two 0 degree plies near the surface and in the midplane in the axial and transverse direction. The dimensions of the coupons will be 12in X 1in. The sensors will have a 6in gage length. Several of these coupons have been fabricated and will be tested soon. The results of the interferometric data will be compared with surface mounted strain gauges. This task will identify potential limitations and problems such as microbend loss and hysteresis associated with the Mach-Zender Interferometer system. It will also demonstrate the capabilities of the composite embedded fiber optic strain sensors in smart structures.

The fourth task is with Dr. Dave Kranbuehl from the College of William and Mary. The objective of this task is to develop frequency dependent electromagnetic sensor (FDEMS) techniques for insitu monitoring of the chemical structural integrity of composite structures. The FDEMS will also be used to determine any degradation to the structure caused by exposure to atomic oxygen, thermal cycling, UV and high energy radiation, and stress-strain extremes. This task is divided up into four phases. The first phase will demonstrate the feasibility of using the FDEMS sensor to detect any degradation due to exposure to atomic oxygen and thermal extremes of the space environment. The second phase will develop relationships between the FDEMS sensor and mechanical failure measurements and weight loss. The third phase will determine the usable life of neat polymeric resins in simulated space and flight environments. The final phase will involve using the FDEMS sensor for life monitoring of composite parts and coatings in simulated space and flight environments. The expected result of this task is to demonstrate the reliability of the composite part and the use of the FDEMS sensor to monitor the structural integrity during the life of the structure.

The final task under the in-house project is a joint effort between the AL and Dr. Mike Gorman from the Naval PostGraduate School. The objective of this task is to evaluate the performance and sensitivity of the new embedded sensors to more conventional sensors and theoretical calculations. Various tubes and flat beams will be fabricated at the AL with different types of sensors such as piezoelectric crystals, fiber optics, strain wire, and NiTiNOL wire embedded in them. These beams will then be tested both at the AL and NASA LaRC to determine the performance of the embedded sensors. After completion of the first tests, the specimens will be tested at the Naval PostGraduate School using more conventional sensors such as accelerometers, strain gauges, etc... in order to calibrate the embedded sensors and to determine their performance and sensitivity. The results of both tests will be compared to theoretical calculations for the specimens.

4. SUMMARY

Once the feasibility of smart structures/skins is demonstrated, the AL plans on incorporating this technology into near term and future applications. One near term application for smart structures/skins is the large space structure ground test facility called ASTREX being developed at the AL. Key members of the test article, which will be the tripod portion of a space-based laser, will be replaced by members with sensors and actuators embedded into them. The test article will then be slewed causing the members to vibrate. The sensors will then sense the vibrations and the actuators will dampen out the vibrations. The performance of embedded sensors and actuators will then be compared the performance of conventional sensors and actuators such as accelerometers and control moment gyros.

The AL is also planning some future projects in the area of smart structures/skins. One such project is titled, "Embedded Health Monitoring Demonstration." The objective of this project is to evaluate various sensing events such as strain, stiffness, temperature, and chemical aging to develop accurate life prediction models of space structures. This project will expand on the results of the ACESA contracts to use the vibration sensors from health monitoring. The payoff of this project is to be able to replace spacecraft by need or cause rather than by time or statistics.

Some possible future applications of smart structures/skins include various AF, NASA, and SDI space structures. Some future space structures that may use smart structures/skins include Space Based Radar, Space Station, and Space Based Laser. Each of these large space structures (LSS) will require some active control system to dampen any natural vibrations and those caused by rapid movements. Also each of these LSS will require some type of health monitoring system to detect any damage which occurs to the structure.

Some areas that future research and development need to address are the connectivity of the sensors and actuators from one member to another. How will the sensors and actuators connect when one member is attached to another? Another area that needs to be addressed is reliability and maintainability of the embedded sensors and actuators. How can the sensors and actuators be repaired or replaced once embedded into the material?

The AL is committed to develop the technology area of smart structures/skins. We have developed an extensive effort in this area and we plan on expanding our effort in the future. We will make every possible attempt to incorporate this technology into future applications.